Plasma Instabilities and Isotropization in Heavy-Ion Collisions

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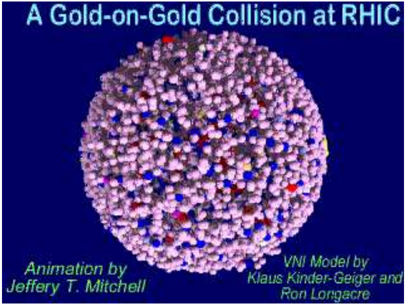
Outline

1. Introduction
   - CGC Initial Conditions
   - Effects of Expansion I: Hard-(Expanding)-Loops
2. A Weibel Instability in the Melting Color Glass Condensate
   - Effects of Expansion II: Classical Chromodynamics on the Lattice
3. What about Hydro

Motivation: Au+Au Collisions at RHIC



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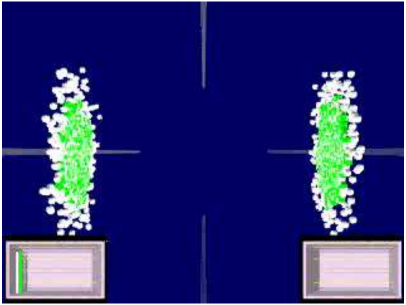

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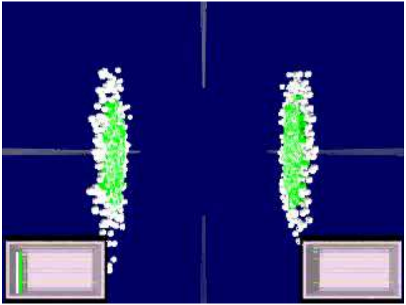

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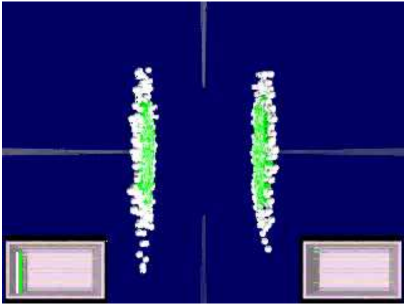

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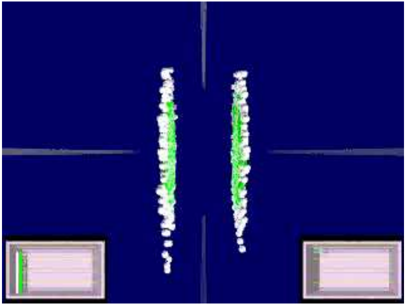

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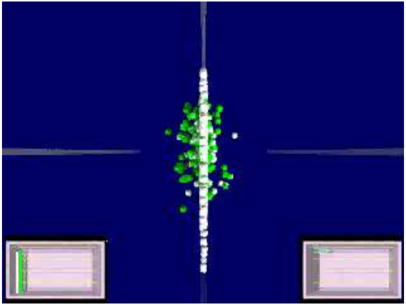

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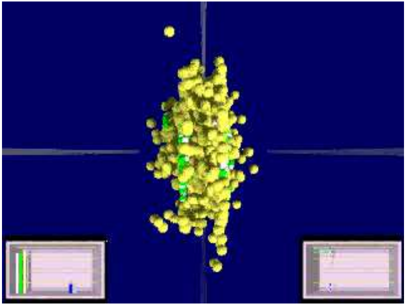

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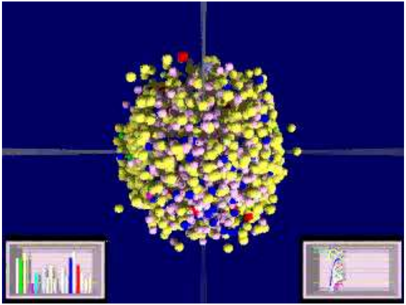

Outline

Initial Conditions for Heavy-Ion Collisions
MV-Model

- Color source for a large nucleus moving (nearly) with $v \sim c$

$$J_a^\mu = \delta_+^\mu \rho_a(x_\perp)\delta(x^-)$$

  where $x^\pm = (t \pm z)/\sqrt{2}$.
- Color charges ρ_a in the McLerran-Venugopalan-Model:

$$< \rho_a(x_\perp)\rho_b(y_\perp) >= g^2\mu^2\delta_{ab}\delta^2(x_\perp - y_\perp)$$

Model of a Heavy-Ion Collision

- Consider two infinitely large nuclei

$$J^\mu_a = \delta^\mu_+ \rho^{(1)}_a(x_\perp)\delta(x^-) + \delta^\mu_- \rho^{(2)}_a(x_\perp)\delta(x^+)$$

- Nuclei interact only at $\tau = \sqrt{2x^+x^-} = 0$
- Property of $A^\mu(\tau = 0)$: independent of rapidity $\eta = \mathrm{arctanh}\frac{z}{t}$
- "Boost-Invariance of the fields:" Can solve YM-equations on 2+1 D lattice

Initial Conditions for a Heavy-Ion Collision

More Realistic Model

- Exact rapidity-invariance not achievable because of
- geometric effects (cannot accelerate Au to $v = c$)
- quantum effects (BFKL predicts sizeable rapidity fluctuations)
- => Sources will not be confined to the light-cone (no exact δ-functions)
- There will be “initial” fluctuations in rapidity (though size& spectrum currently unknown)

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Initial Conditions – Summary

After the collision,

- the typical transverse gluon momentum will be $\langle p_\perp \rangle \sim Q_s$ (saturation scenario)
- the typical longitudinal gluon momentum will be $\langle p_L \rangle \sim \tau^{-1}$ (expansion)
- there will be non-vanishing fluctuations in rapidity

Outline

Hard-Loops in Anisotropically Expanding Geometry

- Momentum anisotropy leads to plasma instabilities; Hard-Loops in “static” geometry (Mrowczynski, PR, Strickland, Arnold, Lenaghan, Moore, Yaffe, Manuel, ...), cf talks by M. Strickland and G.D. Moore
- Numerical studies in systems without expansions (see above + Dumitru, Nara, Bödeker, Rummukainen)
- Hard-Loops in Anisotropically Expanding Geometry: PR and A. Rebhan, hep-ph/0605064

Analytic Solutions in HEL (Hard-Expanding-Loops)

- Introducing a Fourier transform in space-time rapidity,

$$A^i(\tau,\eta) = \int \frac{d\nu}{2\pi} \exp(i\nu\eta)\widetilde{A}^i(\tau,\nu),$$

- at $\tau \gg 1$, one finds that $\nu \ll 1$ modes are stable

$$\widetilde{A}^i(\tau,\nu) = c_1 J_0\left(2\sqrt{\mu\tau}\right) + c_2 Y_0\left(2\sqrt{\mu\tau}\right),$$

  while hard modes $\nu \gg 1$ behave as

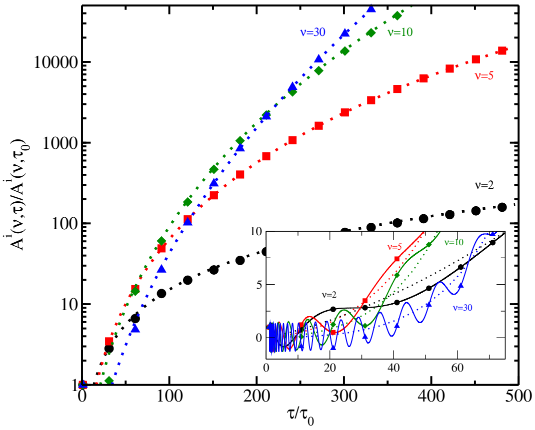
$$\widetilde{A}^i(\tau,\nu) = c_1\sqrt{\tau} I_1\left(2\sqrt{\mu\tau}\right) + c_2\sqrt{\tau} K_1\left(2\sqrt{\mu\tau}\right),$$

- Asymptotic behavior:

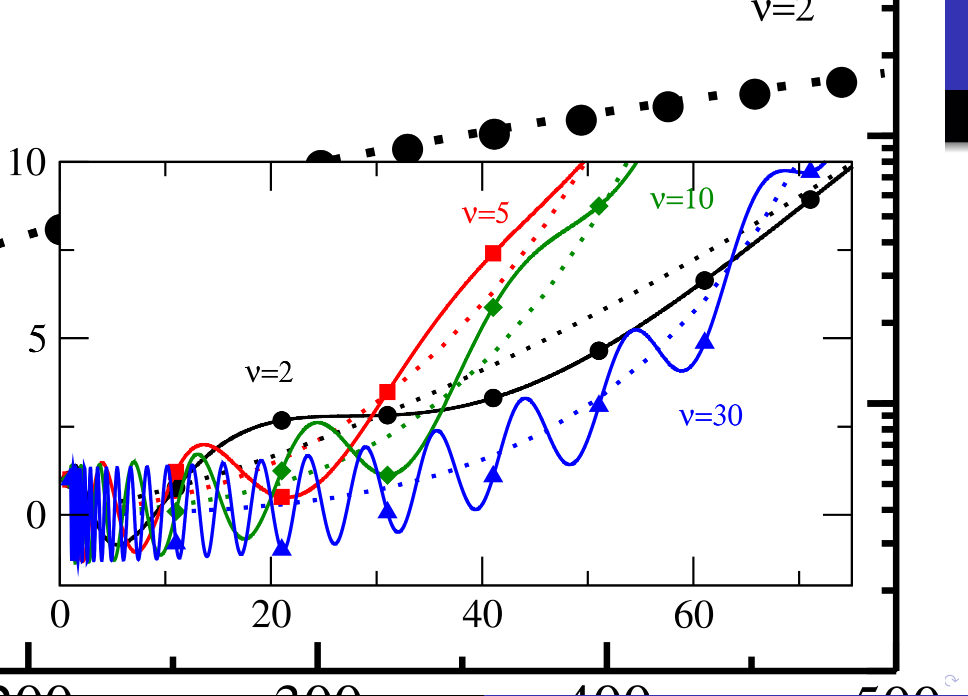
$$\widetilde{A}^i(\tau) \sim \tau^{1/4} \exp\left(2\sqrt{\mu\tau}\right).$$

PR+A.Rebhan, hep-ph/0605064

How long does it take?



PR+A.Rebhan, hep-ph/0605064

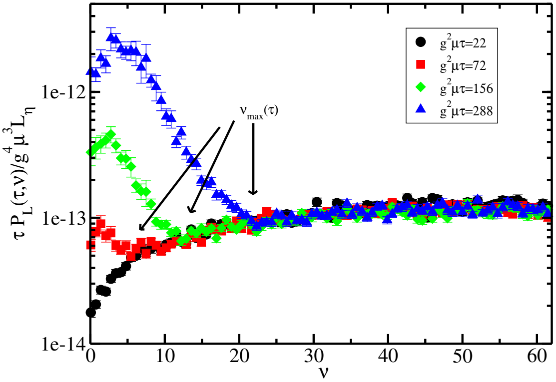


ν=5
ν=10
ν=2
ν=30
10
5
0
0
20
40
60

Outline

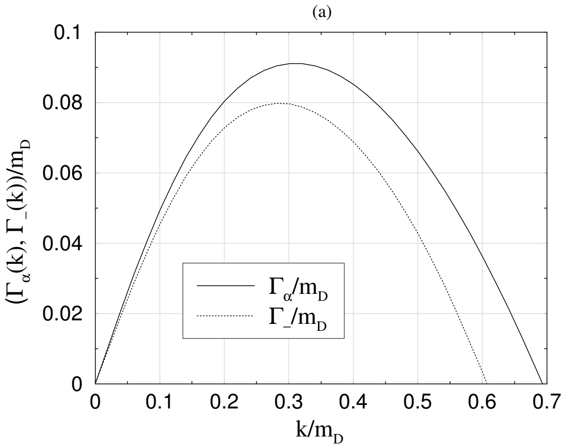
Simulating the Melting Color Glass Condensate in 3+1D

Longitudinal Mode Spectrum



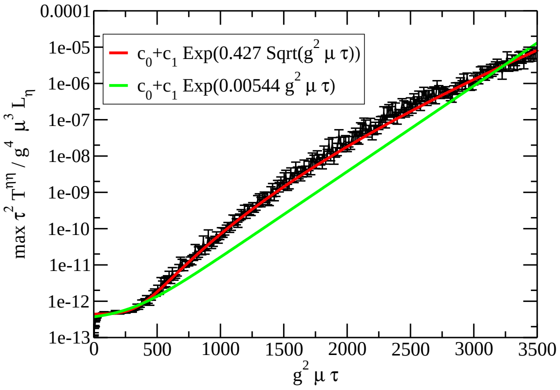
PR+R.Venugopalan, hep-ph/0605045

Similarities to Hard-Loop Results



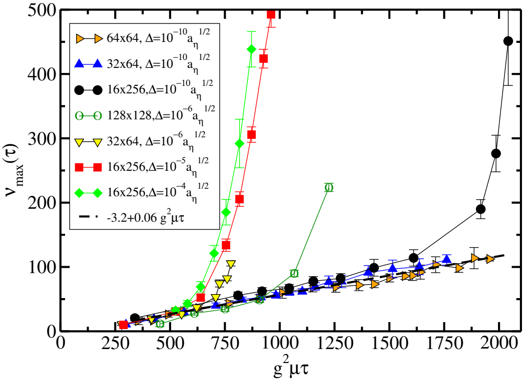
PR+M.Strickland, PRD 68 (2003)

Time Evolution of Gauge Modes



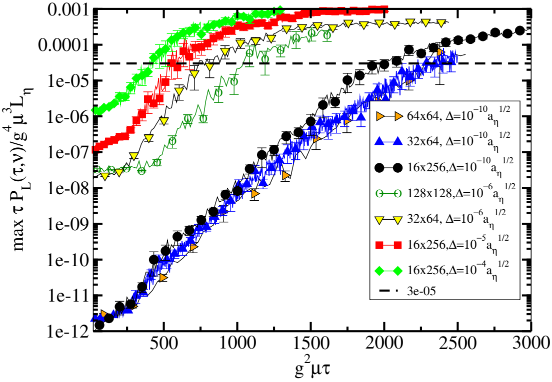
PR+R.Venugopalan, PRL96 (2005)

Time Evolution of $\nu_{\max}$



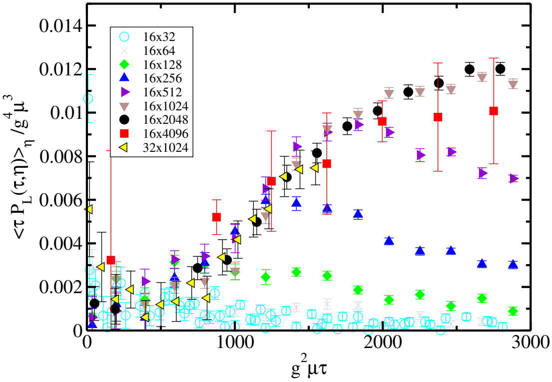
PR+R.Venugopalan, hep-ph/0605045

Relation to Fluctuation Amplitudes



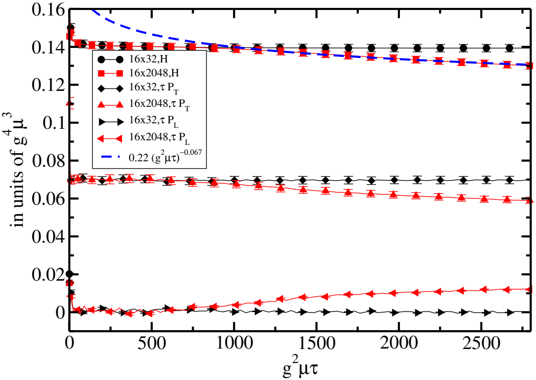
PR+R.Venugopalan, hep-ph/0605045

Buildup of longitudinal pressure



PR+R.Venugopalan, hep-ph/0605045

Towards Isotropy



PR+R.Venugopalan, hep-ph/0605045

Mini-Summary

- The QGP is colored, so mean-field fluctuations (even if they are tiny initially!) can become important
- Because of longitudinal expansion, plasma-instabilities are generic to heavy-ion collisions
- Plasma-instabilities make the system more isotropic
- Whether plasma-instabilities lead to fast ($\tau < 1$fm/c) isotropization heavily depends on the initial conditions
- With CGC initial conditions, probably not at RHIC

Why Viscous Hydro is Interesting

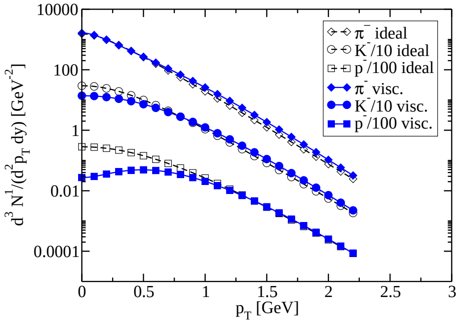
- Ideal hydro fits to data *require* isotropic system at fairly early times ($\tau < 1$ fm/c)
- However, this is not the case for *viscous* hydro

$$T^{\mu\nu} = \begin{array}{cc} & \begin{array}{cccc} t & x & y & z \end{array} \\ \begin{array}{c} t \\ x \\ y \\ z \end{array} & \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \frac{2}{3}\frac{\eta}{\tau} & 0 & 0 \\ 0 & 0 & p + \frac{2}{3}\frac{\eta}{\tau} & 0 \\ 0 & 0 & 0 & p - \frac{4}{3}\frac{\eta}{\tau} \end{pmatrix} \end{array},$$

- Is there room for viscosity at RHIC?

Causal Relativistic Viscous Hydro Particle Spectra

$\eta/s \sim 0.3$, Bjorken flow only



R. Baier, PR and U.A.Wiedemann, hep-ph/0602249

Summary

- If a QGP is produced in HIC, there will generically be instabilities
- Whether they are responsible for fast isotropization depends on the initial conditions
- A possible “alternative” to fast isotropy could be a moderate viscosity for the QGP
- Besides isotropization, there may be many more phenomena driven by non-Abelian plasma instabilities (Kolmogorov cascades, UV avalanche,...)

- Outlook
  - Quantify effects of non-Abelian saturation & expansion
  - Experimental observables (jet-shapes?)